

Studies of Mine Burial in Coastal Environments

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LONG-TERM GOALS

The U.S. Navy needs reliable predictive capabilities for mine burial in shallow coastal environments in support of developing doctrine algorithms for mine countermeasures (MCM). The long-term goal of our research program is to improve scientific knowledge pertinent to fluid dynamic and sedimentary processes related to the burial of mines with the hope of significantly improving the predictive capabilities of MCM operations. The main focus is non-walking ship mines of cylindrical shape placed in the coastal shoaling zone. Theoretical, laboratory experimental and numerical tools will be employed in the studies.

OBJECTIVES

A review of literature reveals the need for integration of knowledge from different disciplines to support the development of physics-based models for mine burial. The important parameters to consider are the near and far field environmental factors and coupled sediment (soil)-structure-flow interaction processes. The scientific objectives of our research have been selected to address these aspects, in particular: (i) to study the evolution of an initially flat sandy beach under nonlinear progressive waves; (ii) to investigate the long-term evolution of bottom topography in relation to mine burial scenarios, and (iii) to document the behavior of model mines in the shoaling zone. Special attention is given to: (i) water motion and ensuing scour around cylindrical mines placed on a sandy slope under progressive nonlinear waves; (ii) morphodynamics of sandy beds under water waves; (iii) delineate conditions for periodic or lasting burial of model mines; and (iv) velocity measurements around short cylinders on a plane bottom.

APPROACH

Tools of laboratory and theoretical fluid dynamics were employed to better understand and model hydrodynamic processes related to morphodynamics of sandy bed and associated mine burial. The major focus was on the physical understanding and parameterizations of flow around mines and ensuing scour/burial processes, with the goal of incorporating them into probabilistic models (expert systems).

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WORK COMPLETED

Our previous studies were concentrated mostly on the behavior of disk-shaped and spherical model mines on horizontal and sloping beaches under oscillatory flows [1-4]. In the present work, relatively large cylindrical mines placed on a sandy slope under progressive shoaling waves in a large wave tank (Fig.1) were considered. In parallel, simulations were conducted using similar (in size) numerical wave tank. Experiments were also carried out in a towing tank constructed to study the near field 3-D flow of a short cylinder placed on the solid bottom boundary of an oscillatory flow.

Quantitative data were obtained using high-resolution video cameras, three-component acoustic Doppler velocimetry (ADV), "structural" light technique and other state-of-the-art diagnostic methods such as particle image velocimetry system (PIV).

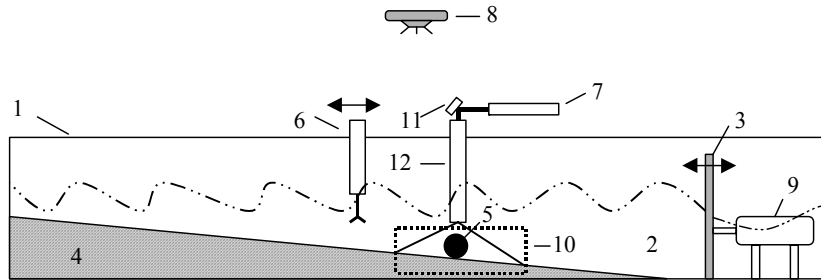


Figure 1. Schematic of the ASU wave tank: 1 – tank, 2 – water, 3 – vertical wave-maker (frequency - ω , amplitude of horizontal displacement - ε_0), 4 – sloping bottom (slope = $1/24$), 5 – mine, 6 – acoustic Doppler velocimeter attached to carriage, 7 – laser, 8 – photo/video camera, 9 – hydraulic system to move wave maker, 10 – view frame of a digital camera which is connected to a computer, 11 – mirror, 12 – light guide with splitting optics under the water level. Size: 32x1.8x0.8 m.

RESULTS

Our recent findings are presented in detail in [5-10], and they can be summarized as follows: (i) A scour/burial regime diagram for cylindrical mines as a function of two main parameters (Keulegan-Carpenter, KC, and Shields parameter, Sh) was developed experimentally and explained theoretically; (ii) Semi-empirical formulae, which permit the calculation of scour depth as a function of time, the equilibrium maximum scour depth and conditions of cylinder burial were obtained; (iii) Experimental data on ripples instabilities and ripple drift were collected and explained; (iv) Data on the characteristics and dynamics of the bedform, including the down-slope propagation speed of ripple front, ripple growth and flow around ripples were collected and explained; (v) A self-similar relaxation (response) was identified for the water-sand-mine system under different perturbations.

Our results show the importance of intense horseshoe tip vortices (Fig.2) generated periodically in the lee side of a short cylinder placed on the plane bottom of an oscillatory flow. The detailed topological structure and characteristics of these vortices are important in understanding and parameterization of large scour observed around short (mine-shaped) cylinders on a sandy bed (Fig. 3). The literature on the topic of oscillatory flow around a short cylinder located on a solid bottom is practically non-existent, and to this end a series of experiments was conducted as described below.

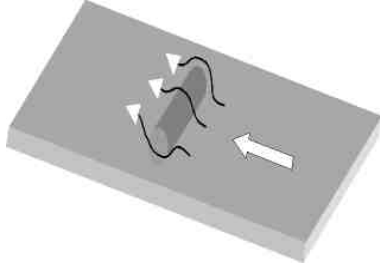


Figure 2 (left): A schematic showing the formation of energetic horseshoe tip vortices at the lee side of a cylinder during the onshore water motion (large arrow).

Figure 3(right): A photograph of the expanded scour pattern (regime III) around a cylinder. The onshore direction is to the left. Experimental parameters: $D = 8$ cm, $KC = 10$, $Sh = 0.27$ (from [7]).

The experiments were conducted using a towing tank (Fig. 4) equipped with a PIV system. A model cylindrical mine (aspect ratio = 5; diameter D) was mounted on a flat bottom of a carriage that could move steadily or oscillate with a horizontal velocity $U(t)$ in water. A powerful laser beam, transmitted through a fiber optic cable and formed into a light sheet *via* a cylindrical lens, was used for illumination of the flow. The flow was visualized by small particles, and streak-line photography was used to infer flow patterns. Detailed quantitative data on the velocity/vorticity fields were obtained by PIV. The video/still cameras as well as optics were configured either at the top or the side of the moving carriage depending on the view of interest.

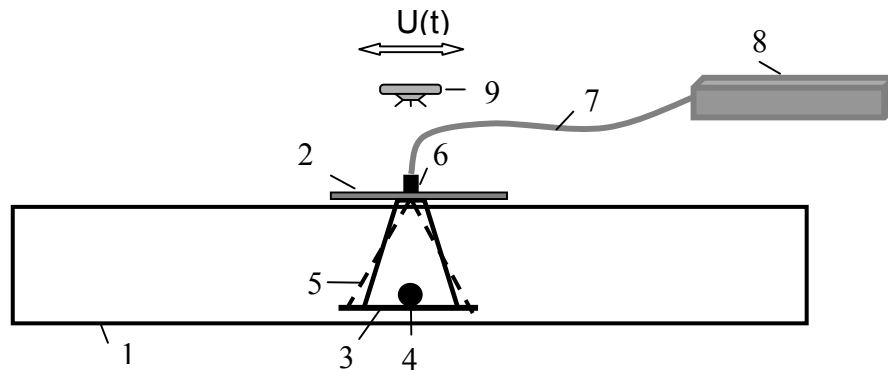


Figure 4: Schematic of the towing tank: 1 – tank with water, 2 – computer controlled platform moving with velocity $U(t)$, 3 – Plexiglas carriage with two end walls and bottom, 4 - short cylinder at the bottom of carriage, 5 – narrow vertical (for top view or horizontal) (for side view) light beam from cylindrical lens (6) connected via flexible fiber optic cable (7) to stationary water cooled laser (8), (9) – video / photo camera. Size: 4x0.4x0.4 m.

Streak line photographs in Fig. 5 show a typical side view of the flow patterns at a cross section through the center of the cylinder. When the water moves from right to left (Fig. 5a) at (approximately) its maximum speed, an intense horseshoe tip vortex (shown by the arrow) is formed within a narrow

wake. The top view in Fig. 6 shows a horizontal cross section of this vortex at a distance $D/2$ from the bottom. Two counter-rotating tip vortices can be seen in this photograph; the resulting vortex lines join each other to form a horseshoe vortex. When the water velocity decreases the vortex detaches from solid bottom (Figs. 5b). It becomes very large and energetic when the water velocity tends to zero (phase - $\pi/2$, Fig. 5c). In oscillatory flow, this process recurs with a vortex emanating periodically from both sides of the cylinder. Because of the self-induced flow, the vortex moves toward the cylinder (Fig. 5c) and, depending on the flow parameters, it may pass the cylinder before water starts moving to the right.

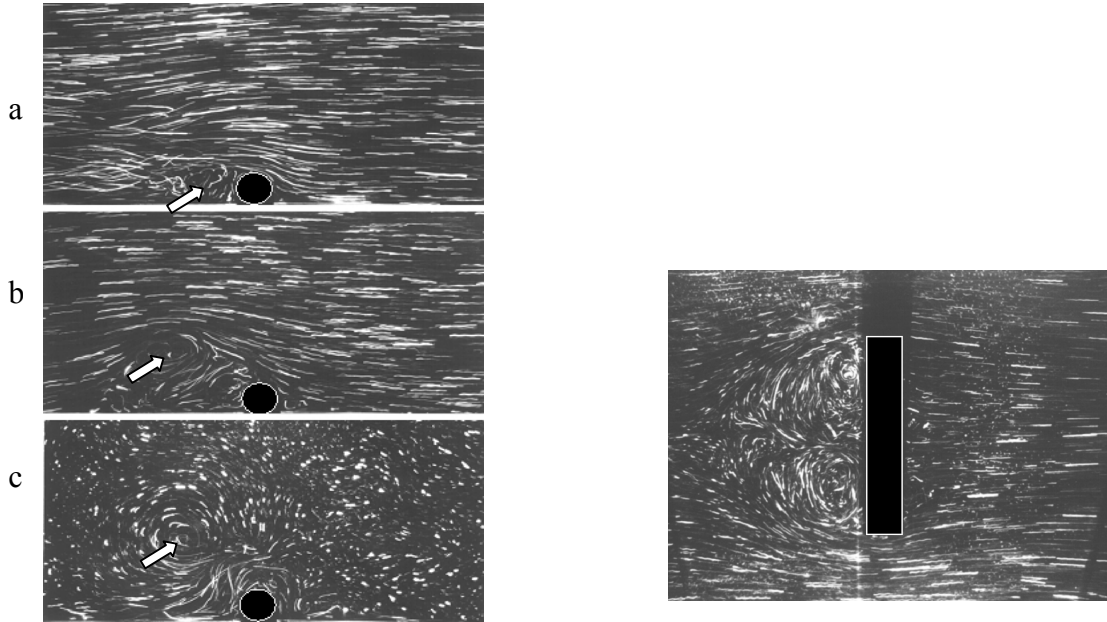


Figure 5 (left): Side-view streak line photographs at three different phases of oscillatory flow around a short cylinder. Experimental parameters: $D = 2$ cm, $L = 4$ cm, $KC = 28$ and $Re = 4500$.

Flow phases: a - 0, b - $\pi/4$, c - $\pi/2$.

Figure 6 (right): Top-view streak line photograph illustrating energetic tip vortices at a distance $D/2$ from the bottom. Experimental parameters are the same as in Fig. 5 and flow phase - 0.

A typical instantaneous PIV velocity map (side-view) is shown in Fig. 7. Red to blue color mapping corresponds to the vorticity field and arrows of different length show the velocity field. A large counter clockwise rotating vortex (a cross section of the detached horseshoe tip vortex) can be clearly seen in this figure.

IMPACT/APPLICATIONS

The scour and burial of large cylindrical objects, such as anti-ship mines, on a sandy sloping bottom submerged in the wave boundary layer typical of coastal shoaling zone is not well understood from a fundamental point of view. This project has made fundamental advances in this regard by utilizing integrated laboratory and theoretical/numerical approaches. The results are of general validity, and

hence will be of utility in many oceanic fluid/structure interaction problems, including extrication of bodies, coastal conservation, scour around pipelines and pillars in coastal waters.

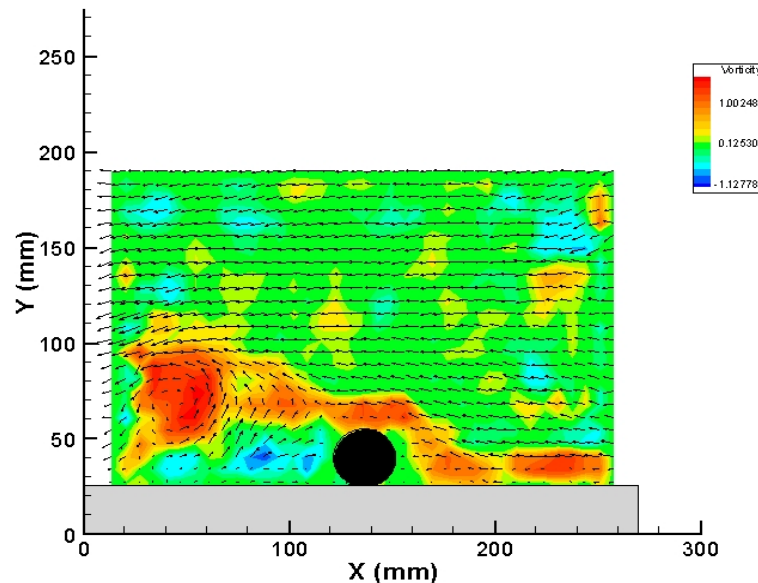


Figure 7: *A typical PIV velocity/vorticity map (side-view). Red to blue color mapping corresponds to vorticity field and arrows of different length show the velocity field (the background velocity in this case is 2 cm/s). Experimental parameters: $D = 3$ cm, $KC = 10$, $Re = 9500$.*

TRANSITIONS

The results have been transmitted to the Johns Hopkins APL group who are developing an expert system in support of MCM operations. Also, some of the modelers (Scott Jenkins, Chiang Mei) are using our results in their research/development work. The results will soon be placed in perspective of those from the Indian Bend Mine Burial experiment, which are now available to the PIs.

RELATED PROJECTS

The results obtained on scour rates and flow regimes will be compared with operational mine burial models: WISSP, NBURY and DRAMBUI. We have already started collaboration with Carl Friedrich (College of William and Mary) who is familiar with the details of these models. Also, the results are being compared with the predictions of Inman/Jenkins research model. We also have active collaboration with Chiang Mei's group (MIT) with regard to the evolution of bedforms, in particular, instability mechanisms pertinent to them.

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HONORS/AWARDS/PRIZES

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